Kinesthetic Feedback for Robot-Assisted Minimally Invasive Surgery (Da Vinci) with Two Fingers Exoskeleton

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Abstract. Minimally Invasive Surgery and, in particular, Robotic Minimally Invasive Surgery may benefit from the integration of Haptic device: here we propose a preliminary study on a two-finger exoskeleton for kinesthetic feedback of surgeon thumb and index finger while controlling a Da Vinci Robotic Device through its Master Tool Manipulator (MTM). Simulation of contact between rigid and soft objects with the Patient Side Manipulator (PSM) are integrated with Force Feedback on the MTM coupled with the exoskeleton.

Keywords: Haptic device · Kinesthetic feedback · Da Vinci

1 Introduction

Minimal Invasive Surgery (MIS) is a surgical technique started during the mid 20th century. MIS uses specially designed surgical tools with multiple Degrees Of Freedom (DOF) wrist. The tools are long but very small, which enables their use inside small incisions of a patient skin. Such system benefits in the reduction of surgical trauma to the tissue decreased pain during surgery and the time to heal the wound. It also creates smaller visible scars compared to conventional surgical procedures. However, the loss of direct touch and contact with the operation site creates some disadvantages for the surgeon [1]. During MIS, in fact, the surgeon will not be able to assess the tissue properties by direct touch or palpation.

Even though multiple DOF endo-wrist (Fig. 1) helps to access the operation site in many directions, the tools need to move at the fixed point of the incision; therefore the DOF motion by the tool is lost, decreasing dexterity inside the operation site. Direct hand-eye coordination is also lost in such scenarios, which makes complex tasks such as knot tying very time consuming and require intensive training.

Robot-assisted Minimally Invasive Surgery (RMIS) was introduced to help reduce some of the disadvantages of MIS. RMIS can improve the accuracy and dexterity of the surgeon. It also minimizes trauma and pain to the patient. Current RMIS system enables hand-eye coordination through motion scaling and tremor filtering. However,

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when the surgeon operates the gripper, there is no feedback about the amount of forces exerted other than tissue deformation and other visual cues. Thus, the lack of direct haptic feedback is still a limitation in most of the RMIS systems.

Haptic Feedback - i.e. force and tactile feedback - can be provided from tool-tissue interaction forces and torques during grasping, palpation and tissue manipulation. Such kind of feedback may significantly improve patient safety and reduce operation time in RMOS. Excess grip force, in fact, could result in tissue damage for the patient [3] and also hand fatigue for the surgeon [4]. On the other hand, insufficient grip force may cause slipping of the tissue and increases the task difficulty.

Previous studies have explored different tactile and force feedback methods to provide Haptic Feedback for the surgeon. Many studies have shown that force feedback is essential in telesurgery [5–7] and it is favourable by the operator compared to other types of feedback, mainly visual and auditory [8–10]. Macfiled et al. [11, 12] demonstrated that the mechanoreceptors in the fingertip are essential for grip force control. The importance of tactile feedback for grip force control has been also largely explored [8, 13–15].

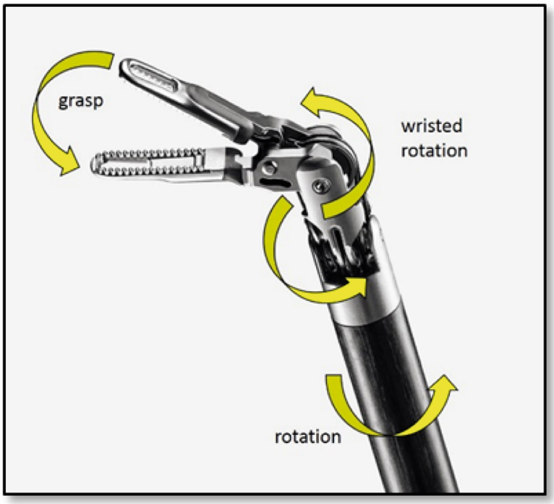

Fig. 1. A typical multi-DOF Endowrist for RMIS (modified from [2]).

In this paper we present a new design of a 2-fingers exoskeleton for haptic feedback combined with one of the most worldwide used robotic device: the application of this haptic Exoskeleton to display gripping force feedback for operation using the Da Vinci Surgical Research Kit (DVRK) is studied. Such kind of force feedback can reduce unintentional tissue injuries, and benefits the surgical procedure since it has been shown that force feedback reduces the grasping force in robot-assisted surgery.

2 Haptics in RMIS

Haptics generally describes touch feedback, which consists of Kinaesthetic (force) and Cutaneous (tactile) feedback. Currently, most RMIS systems do not include haptic feedback system however many research and evaluations are going on to include haptics in commercial and research prototype RMIS system. Nevertheless those systems which include haptics mostly provide only force feedback, with limited reliability. Some researchers have also developed tactile feedback systems for RMIS, but some of these implementations are still technologically limited since tactile feedback inherently requires spatially distributed sensing and display of tactile information. An example of the interaction between devices and operators in a RIMS scenario is reported in Fig. 2.

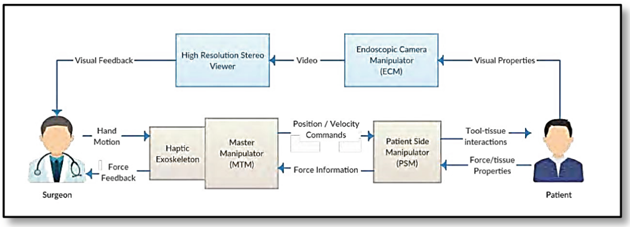

Fig. 2. Information flow in RMIS with haptic feedback.

The main challenges of Haptics in RMIS is the need of haptic techniques and sensors on the user and patient sides to acquire haptic information [16–18]. These sensors need to be very small to be fitted with the current surgical tools without affecting the manoeuvrability and dexterity of the tool itself. Commercially available force sensors are useful in measuring forces and torques produced during teleoperation. However, the size of these sensors has to be minimized to allow its use in the surgical environment. Apart from constraints in size and geometry, bio-compatibility and sterilization are other demanding constraints.

Some researchers have created specialized grippers with force sensors attached to the jaws. An ideal option would be estimating the forces applied indirectly without using force sensors on the gripper. The other challenge is the haptic display used to convey the information to the surgeon. Kinesthetic or force feedback system provides resolved force to the hand via force feedback devices. However, the fidelity of such force feedback devices is limited due to the dynamics force created by higher inertia and friction that are difficult to account or to measure. Accurate force feedback requires also a set of accurate dynamic models of the master and patient side manipulator to guarantee the stability of the system and the transparency of the force feedback. The displayed force feedback can also be affected by time delays due to the computational time and the delay of the transmission.

Even though, force feedback appears to be enough in many surgical procedures, tactile information such as contact location, finger-pad deformation, and pressure distribution can be necessary particularly during palpation. Therefore, the addition of tactile, haptic devices could also improve the operation procedure.

Another approach is using sensory substitution methods such as audio feedback, visual and graphical feedback or other forms like vibrotactile display [18].

Visually observing the tissue properties during the motion of the surgical instrument can also be used as feedback. However, such systems should be designed carefully not to distract the surgeon's view of the patient.

2.1 The Da Vinci Research Kit (DVRK)

2.1.1 Overall Configuration

The DVRK is a research platform from Intuitive Surgical: it is used to enhance collaborative research and development of new technologies for RMIS.

At the Antal Bejczy Center for Intelligent Robotics, Obuda University, a DVRKT system is available; the system is made of the following components (Fig. 3):

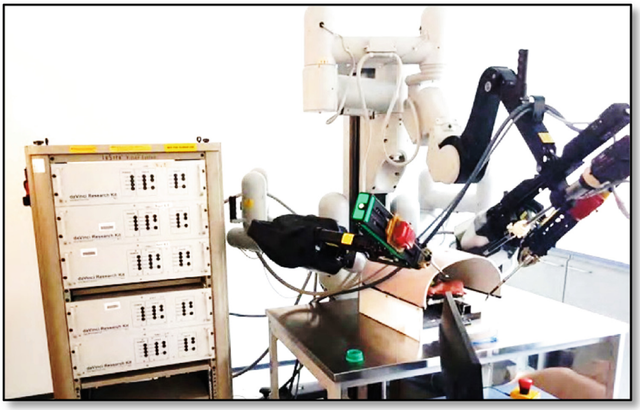

Fig. 3. The DV Research Kit (DVRKT) at Antal Bejczy Center for Intelligent Robotics.

- two Master Tool Manipulators (MTMs)
- two Patient Side Manipulators (PSMs)
- one High-Resolution Stereo Viewer (HRSV)
- one foot pedal tray and an hardware interface between the two consoles
- one Endoscopic Camera Manipulator (ECM)
- one Control Electronic System which is based on IEEE-1394 FPGA boards and Quad Linear Amplifier (QLA).

An overarching telerobotic software is available in order to control the DVRKT. This software is based on the Open Source Robotic Operative System (R.O.S.). It has different functional layers, namely the Hardware Interface (I/O), the Low-Level Control (e.g. PID), the High-Level Control, the Teleoperation system and, finally, the Application. Computer Assisted Intervention Systems (Cisst) libraries and Surgical Assistant Workstation (SAW) are used. The Low-Level Control layer consists of the PID joint controllers (one for each manipulator). The High-Level Control is provided by two components that are specific for the da Vinci MTM and PSM. These provide the forward and inverse kinematics, the trajectory generation, and the gripper control. They also manage the state transitions for the Da Vinci manipulators, such as the homing (MTM and PSM), the engaging the sterile adapter plate (PSM), and the engaging the instrument (PSM). The Teleoperation layer is provided by two instances of a general-purpose SAW component that each connect one MTM to one PSM. Finally, the Application layer is provided by a console application with HRSV that emulates the master console environment of the DVRKT (Fig. 4).

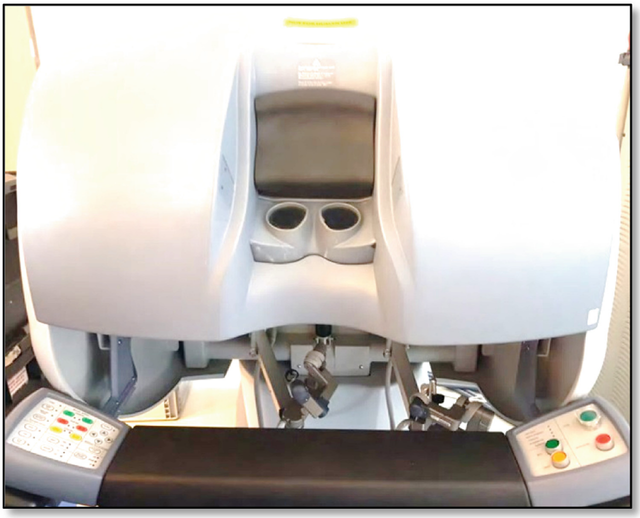

Fig. 4. The DVRKT HRSV console and master manipulators.

2.1.2 Gripper and Tool Configuration & Software Configuration

A variety of different and multi-purpose tools are available for the DVRKT. In this application we will focus on one of the most commonly used tool, the Endowrist. This gripper, as it is shown in Fig. 1, is a 4 DOF surgical tool, which is commonly used by Da Vinci operators. The tool is composed of tendons and pulley, which allows to orient the gripper around different rotational axes. The tendon actuation of the Endowrist introduces some non-linearities, which cause some challenges while modelling and controlling the device.

The R.O.S. software which is available to control the DVRKT provides a set of libraries and utilities. Thanks to these libraries, communication between different robot control processes in one computer or across multiple computers are available: in this study, the position sensing and force feedback controllers are developed as ROS topics that publish the robot state in ROS messages and accept commands by subscribing to ROS messages. An overview of the block diagram of the sensing and control software is reported in Fig. 2. Figure 5 also shows the implementation of the software and its visualizer.

2.2 Force Estimation and Control

Dynamic control of robotic manipulator and haptic devices may be performed via Impedance and Admittance control [19]. Impedance and Admittance Haptic devices interaction control are the most popular type of control system. In the Impedance Control, changes in position are used as an input to compute the output forces; similarly, in the Admittance Control a measured force is used as an input affecting the position and causing a change of the position.

Assuming to implement an Admittance Controller on the DVRKT means that a force sensor has to be fitted on the tip of the DVRK slave tools. However, as it was reported in the Sect. 1 (Introduction), embedding force sensors on a DVRKT tool is not easily achievable due to multiple requirements which involve the size, the biocompatibility, and the need of being able to sterilize the tool before the surgical procedure.

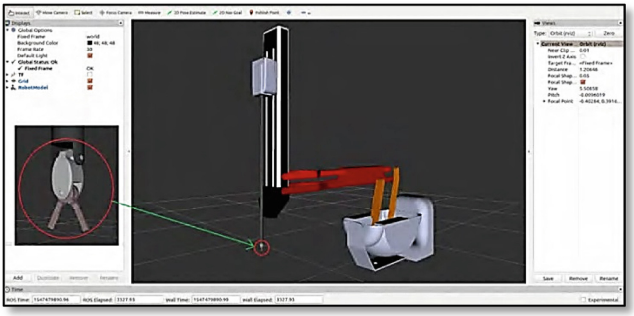

Fig. 5. The DVRK simulation environment under R.O.S. with the RViz 3D visualizer.

On the other side, an Haptic device based on implementing the Impedance Controller should have an intrinsic low friction and inertia. Such a device should be also back-driveable to minimize the dynamic distortion vs. the user's perception. Such a type of Haptic device can be used in applications requiring low force and torques; moreover, these devices have quite a simple design and low cost. For surgical robots with low mass and inertia, the change in desired and actual position of the patient side robot (i.e. where the desired task is a target position of the master manipulator) can be used to display forces which are applied to the environment. However, the reliability of such systems depends on the occurring dynamic and forces. For teleoperated surgical robots, such as the DVRKT, the master manipulator links have relatively large inertial values, in addition, most of the inertial parameter's are not precisely known. This uncertainty makes the impedance haptic feedback quite challenging. Finally, implementing impedance control for force feedback directly from the master DVRKT manipulator is difficult and therefore the role (and need for) an external force feedback device is critical.

The goal here is to develop a technique which uses the change of the position and velocity of the slave gripper in order to compute a proportional amount of force feedback which can be then displayed to the end-user of the DVRKT by means of a haptic exoskeleton.

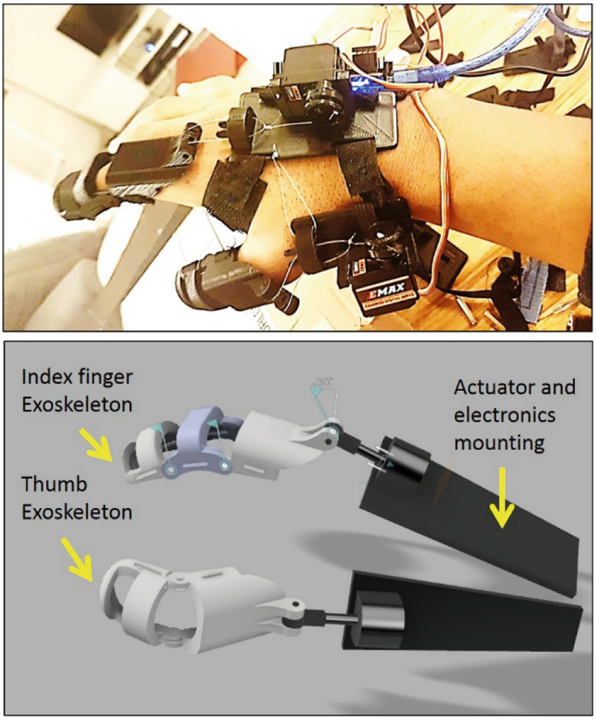

Fig. 6. The 2-fingers exoskeleton prototype and design (top and bottom panels, respectively).

2.3 Design of the Exoskeleton

A two-finger exoskeleton has been designed in order to be coupled with the DVRKT. The exoskeleton has been designed via 3D modelling software and then manufactured through a 3D printing process via extrusion: it is made of Acrylonitrile Butadiene Styrene (ABS) material and equipped with 2 servomotor which are physically connected to the elements of the inter-distal and distal phalanges of the index and thumb through a tendon-driven mechanism. The device is shown in Fig. 6. Details about the design, the sensors & actuators, and the tendon mechanism and kinematics are reported in [20].

Fig. 7. Setting of the exoskeleton when applied to an end-user interacting with the DVRKT patient side manipulators.

2.4 Design of the Controller

Given the aforementioned exoskeleton, we are looking for providing the DVRKT operator with the perception and feeling of grasping. An object, which is gripped between the index finger and thumb should be emulated with a force feedback matching the grip force occurring on the DVRK tool's end effector, i.e. the Endowrist (Fig. 1). Figure 7 shows the setting of the exoskeleton when applied to an end-user interacting with the DVRKT Patient Side Manipulators.

In order to achieve this, the DVRKT and Exoskeleton control system should be designed as a bilateral control system, which receives position commands from the slave robot and reflects the interaction forces on the haptic device.

To this aim, an Impedance control algorithm has been applied for force control of the haptic interface that is coupled with the master robot. During operation, the operator moves the master-haptic interface generating position commands, the impedance between the operator and the haptic interfaces varies dynamically. If the impedance parameters and the dynamics of the master robot are precisely known, a control algorithm can be developed based on the dynamic model of the robot. However, this approach is challenging to implement mainly because of the uncertainty of the dynamic model and parameter variations. The other factor is that the forces that need to be displayed and replicated on the user side are very small compared to the occurring forces of the robot dynamic. In addition, a small positional error can cause a very high force, which results in damaging the user or the robot itself.

Impedance control algorithms monitor the contact forces by controlling the position of the manipulator and using the desired impedance, since the impedance defines the

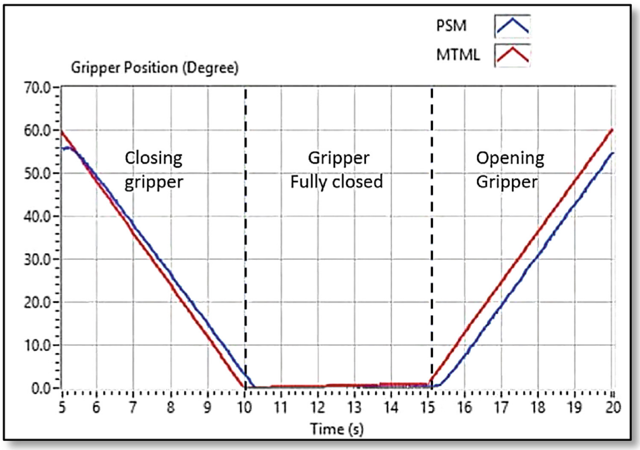

Fig. 8. PSM and MTML profiles under tele-manipulation of the PSM gripper (blue and red lines, respectively). (Color figure online)

relationship between the gripping force and the gripper velocity. For precise operation, the force due to the dynamics (i.e., inertia, friction, and gravity) must be adequately compensated, so that the operator only feels the contact and sliding force of the tool-tissue interaction. Various studies have been done on defining the contact model, the contact stability and performance [21–23]. These researches mainly focused on simplifying the dynamics of the master robot and on compensating the error induced by the simplification [19, 24, 25].

In this paper the haptic feedback is provided through an external exoskeleton device and, therefore, the dynamics of the master robot can be considered as transparent vs. the slave device. During operation, the end-user moves the MTM while grasping the MTM gripper. These movements are tracked and used to compute the control commands of the PSM.

The process is replicated under the R.O.S. environment and a simulation is performed. In the simulation, a PD controller is used to track the position of MTM joint and to implement a control effort, which actuates the PSM motors so that the PSM smoothly follows the MTM position. The linear position of the PSM tools is controlled as it follows:

$$F_{PSM} = K_p \cdot (x_{MTM} - x_{PSM}) - K_d \cdot \dot{x}_{PSM} \tag{1}$$

Where F_{PSM} is the control force effort, x_{MTM} is the position of the MTM, and x_{PSM} is the position of the PSM tool. The control gains are set to be automatically tuned by ROS PID autotune for smooth tracking and stability.

Similarly, the orientation of the PSM tool, including the gripper, is controlled as it follows:

$$\tau_{PSM} = K_p \cdot (\vartheta_{MTM} - \vartheta_{PSM}) - K_d \cdot \dot{\vartheta}_{PSM} \tag{2}$$

Where τ_{PSM} is the control torque effort, ϑ_{MTM} is the angle of the MTM wrist, and ϑ_{PSM} is the angle of the PSM wrist.

2.5 Design of the Gripper Controller

In absence of force feedback, the DVRKT slave gripper simply follows the motion of the DVRKT master gripper and - when an object gets in contact with the environment - such an object is grasped. In this work, a reverse control should be also applied, such as the master follows the motion (i.e. the position and the velocity) of the slave. Thus, our controller uses a PID controller τ_{exo} to generate an input torque effort for the exoskeleton, which is coupled with the master gripper manipulator.

First, let us consider a forward control of the slave gripper by the master. As shown in Fig. 8, when the master gripper is closing or opening, the slave gripper follows the master. The MTM position is used as setpoint (desired value of the controller) whereas the PSM position is used as a state (the actual value of the controlled motion), control effort is estimated based on the error (e) calculated from the difference of PSM and MTM gripper position. It holds:

$$
\begin{aligned}
e_x &= \vartheta_{MTM} - \vartheta_{PSM} \\
e_x &= \dot{\vartheta}_{MTM} - \dot{\vartheta}_{PSM}
\end{aligned} \tag{3}
$$

where ϑ_{MTM} is the angle of the MTM gripper, and ϑ_{PSM} is the angle of the PSM gripper; $\dot{\vartheta}_{MTM}$ is the angular speed of the MTM gripper, and $\dot{\vartheta}_{PSM}$ is the angular speed of the PSM gripper. While the gripper is closing, it holds $e_x > 0$; on the contrary, when the gripper is opening, it holds $e_x < 0$. However, when the object is gripped by the PSM tool, a significant error is introduced, and the PSM will not be able to follow the MTM anymore.

Considering a linear relationship between the deformation of the grasped object and the applied force applied, the error is proportional to the stiffness of the grasped object. Therefore, an error threshold value $e_{x\,threshold}$ is set to estimate the force and torque that should be applied by the exoskeleton. If $e_x > 0$ and $e_{x\,threshold} > e_x$, then the gripper is in contact with an object. Finally a torque τ_{effort} should be applied by the exoskeleton to restrict the movement of the fingertip thereby reducing the error between the MTM and the PSM gripper positions.

$$
\tau_{effort} = K_p \cdot e_x + D_p \cdot \dot{e}_x + I_p \int_0^t e_x dt \tag{4}
$$

Where τ_{effort} is the commanded torque to the exoskeleton motors and the gains depends on the stiffness and damping parameters of the grasped object. The K_p, Dp and Ip values have to be chosen in order to allow a successful grasping under different load conditions while preserving its stability. This mapping allows the end-user piloting the PSM gripper while applying different amounts of grip force to the object.

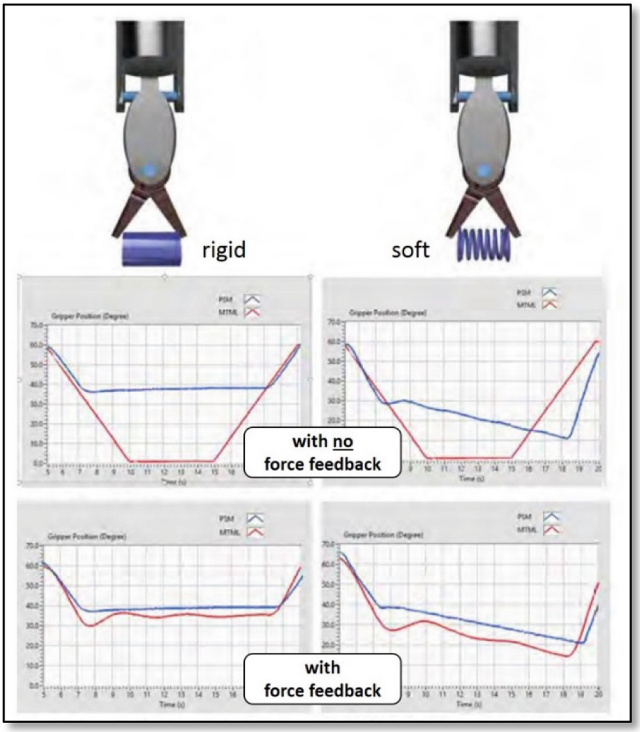

Fig. 9. Force-feedback tele-operation of the MTM and PSM Gripper (red and blue lines, respectively): positions *with* and *without* force feedback (top and bottom panels) for rigid and soft objects (left and right panels) are reported. (Color figure online)

3 Results

A solid and rigid object, as well as a soft components were considered: performed simulation uses both a rigid object and a spring object to mimic different scenarios in which the DVRKT is gripping a body tissue. The dynamic behaviour of the tissue with respect to the external applied forces and torques were modelled as a spring-damper system. According to [201], the desired impedance can be designed through the stiffness parameter, Kd, and the damping parameter, Dd. The motor position in the joint coordinates system can be also controlled by using a PD controller such as:

$$F_m = -K_d \cdot (x - x_s) - D_d \cdot \dot{x} \tag{5}$$

where x_s is the desired position.

Preliminary practical tests were conducted to test the reliability of the system. The communication between the controller and the exoskeleton was handled via USB. Mbed ROS serial node subscribes to the control effort node, and the motor control map the control effort in the range of the maximum and minimum torque needed to actuate the motor. R.O.S. packages were also integrated to test the force feedback and the efficiency of the PID controller algorithms. ROS control nodes and topics used for both the DVRK virtual simulation and the exoskeleton controller were implemented. A DVRK PSM node publishes its time-varying setpoint to the PID controller node which applies corrections via the control effort topic of the exoskeleton controller. The DVRK MTML node also publishes the current value of the MTM position to the state topic. The simulation plots the MTM and PSM gripper positions as shown in Fig. 9.

4 Conclusion and Discussion

In this paper, a novel approach for using a 3D printed exoskeletons as a force feedback device in the DVRKT tele-operated system has been presented. The study was developed in the context of current literature where it was observed that many haptic studies on grip force control are still focusing on cutaneous feedback and not so much on kinesthetic feedback. It is still under discussion how the absence of force feedback on these applications may increase the difficulty of performing remote handling and object manipulation. Many studies have shown, in fact, that a simple force feedback (e.g. providing feedback of the grip) can significantly improve the transparency in robotic-assisted surgery and RMIS. The grip force feedback, in fact, can be employed to enhance surgeons perception of the mechanical properties of the tissue during a RMIS surgical procedure.

In the proposed system of this work we define a single point of contact of the haptic interface in order to display forces to the operator, where these forces mimic the mechanical properties of the tissue getting in contact with the end-effector of the robot (Fig. 9). Even if this is a preliminary integration study, it is important to notice that other studies have also shown that users tend to apply more grip forces in the absence of haptic feedback. Therefore, a proportional amount of force feedback can help these users to reduce their effective gripping force on the patient side. While grasping objects, people may then be able to adjust and fine tune their grip force according to the effective load of force. This result clearly helps in providing enough gripping force and prevent the tissue from being damaged and the tool from slipping. It also avoids damaging the organs due to an excessive force which can also increase the stress and fatigue of the surgeon.

Future works may include a study of the effect of the force feedback when using exoskeleton on the accuracy and time that is needed to complete surgical training procedures. The ergonomic advantage and disadvantages of such haptic feedback systems also needs to be furtherly studied and developed. Psychophysics experiments should also be conducted to analyze the effect of this approach compared to cutaneous feedback and visual feedback only [26]. Further studies must also be completed using teleoperation scheme which uses force sensors at the slave manipulator to support a comparison with the position control methods.

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